

The Transition from Spacecraft Development to Flight Operations: Human Factor Considerations

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Abstract. In the field of aeronautics and astronautics, a paradigm shift has been witnessed by those in academia, research and development, and private industry. Long development life cycles and the budgets to support such programs and projects has given way to aggressive task schedules and leaner resources to draw from – all the while challenging assigned individuals to create and produce improved products or processes. However, this "faster, better, cheaper" concept cannot merely be applied to the design, development, and test of complex systems such as earth-orbiting or interplanetary robotic spacecraft. Full advantage is not possible without due consideration and application to mission operations planning and flight operations. Equally as important as the flight system, the mission operations system consisting of qualified personnel, ground hardware and software tools, and verified and validated operational processes, should also be regarded as a complex system requiring personnel to draw upon formal education, training, related experiences, and heuristic reasoning in engineering an effective and efficient system.

Unquestionably, qualified personnel are the most important elements of a mission operations system. This paper examines the experiences of the Deep Space 1 Project, the first in a series of new technology in-flight validation missions sponsored by the United States National Aeronautics and Space Administration (NASA), specifically, in developing a subsystems analysis and technology validation team comprised of former spacecraft development personnel. Human factor considerations are investigated from initial concept/vision formulation; through operational process development; personnel test and training; to initial uplink product development and test support. Emphasis has been placed on challenges and applied or recommended solutions, so as to provide opportunities for future programs and projects to address and disposition potential issues and concerns as early as possible to reap the benefits associated with learning from other's past experiences.

INTRODUCTION

In the area of robotic space exploration, the Jet Propulsion Laboratory (JPL) is challenged with research, development, and implementation of new, never-before-used technologies to gain further scientific knowledge. NASA's New Millennium Program is comprised of a series of advanced technology in-flight validation missions. (Ridenoure 1996) states that a series of deep space missions are being defined and implemented by JPL concurrently with a series of Earth-orbiting missions defined and implemented jointly by JPL and the Goddard Space Flight Center. Deep Space One (DS1) is the first deep space mission. (Rayman and Lehman 1997) state that like all New Millennium Program missions, the main objective of DS1 is to space-validate a suite of advanced technologies - the payload for these missions. The validation of these technologies gives promise to enabling 21st century space science missions with low development life cycle and mission operations costs.

There are twelve DS1 technologies which include the miniature imaging camera and spectrometer and autonomous on-board optical navigation. However, the most striking of these are arguably the ion propulsion system and advanced solar concentrator array, the combination of which will result in a ten fold or order of magnitude increase in impulse (ratio of force over the propellant mass) over a conventional chemical system. An illustration of the spacecraft in the nominal cruise configuration is shown in Figure 1. During much of the first twenty-six months of the development life cycle, the project was essentially divided into four main elements: the project staff, spacecraft development, science planning, and ground segments as shown in Figure 2. Spacecraft development was on critical path during much of this time period, and due to this focus (Basilio 1998) documented a good number of heuristics instrumental in the eventual success of verifying, integrating, and validating the spacecraft for launch and

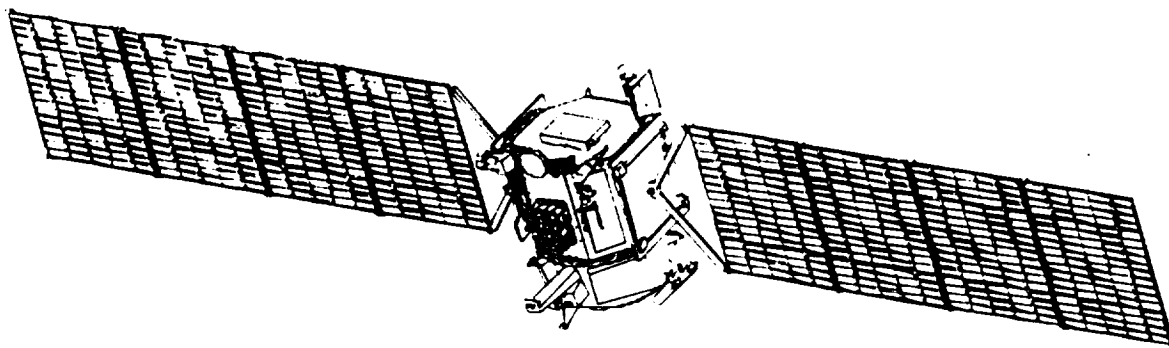


Figure 1 Deep Space 1 Spacecraft with Solar Arrays Deployed

in-flight mission operations. The twenty-seventh month marked the beginning of an organizational transition that re-structured the project team into five main elements comprised of the project staff, science planning and operations, Subsystems Analysis and Technology Validation (SATV), Flight Engineering Team (FET), and the Telecommunications and Missions Operations Directorate (TMOD) support areas to serve mission operations planning and actual in-flight operations needs (see Figure 3). This structure was chosen following a simplified benchmarking technique identified by (Spendolini 1992) in which an organization completes a cursory product or process comparison with similar entities, so as to seek an improvement in it's performance or increase in the probability of it's eventual success. After closer inspection, a knowledgeable individual would readily identify similarities with the Mars Pathfinder Project's mission operations organization.

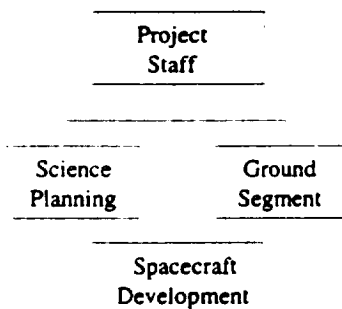


Figure 2 Development Organization

The Mission Operations System (MOS) should be regarded as a complex system given the definition provided by (Rechtin 1991), and as such requires a good

deal of formal education, training, and past professional experience by those involved with it's development. This system, which is comprised of qualified personnel, ground hardware and software tools, and verified and validated operational processes, must prove effective and efficient to be consistent with the "faster, better, cheaper" philosophy. A close examination of the personnel transition process from spacecraft development to flight operations, specifically in the SATV area, was completed to identify important human factor considerations that future programs or projects may find interesting and useful.

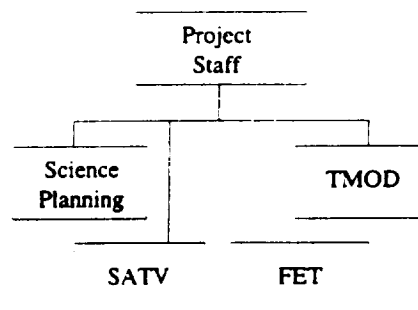


Figure 3 Mission Operations Organization

FORMULATION

Implementation Plan. After having selected a restructured organization with five main elements for the planning and support of in-flight operations, the mission manager unveiled the organization chart at the MOS critical design review meeting in December 1997. Upon receiving the assignment to lead one of the elements the SATV manager soon developed an implementation plan to document his interpretation of

the team's assigned responsibilities, so that the mission manager could review; if necessary, modify; and approve this initial plan prior to proceeding with the details associated with building a competent team. The approved implementation plan was posted on a web-site on the JPL intranet, so that the prospective team members could access the plan and have a better understanding of the new element's responsibilities and what technical and programmatic expertise was being sought by the SATV manager.

Work Package Agreement. A formal contract between the mission manager the SATV manager was created in the form of a typical JPL Work Package Agreement (WPA) in the April 1998 time frame. The WPA summarizes the objectives of the contract, identifies specific responsibilities of the element, itemizes receivables and deliverables with the other elements, lists any known assumptions, includes a

monitor the spacecraft in real-time, and resources permitting, also allows for non-realtime assessment and analysis of the downlinked telemetry data. There are twelve Sun workstations in the MSA and ten in the SATVA that provide access to real-time data monitor and display tools and database query tools. Due to the sensitive nature of the uplink command and downlink telemetry capabilities, these workstations are located on a secure network behind what is coined a "firewall", where a password-type user authentication scheme described by (Tanenbaum 1992) is used for authorized access. Since it was readily apparent that there wasn't a sufficient number of workstations available at any one time to perform simultaneous real-time spacecraft monitoring and non-realtime analysis, even while having a sufficient number of personnel available, the ground data system included the addition of one workstation located on "No Man's LAN (Local Area Network)", so that analysts could perform either real-

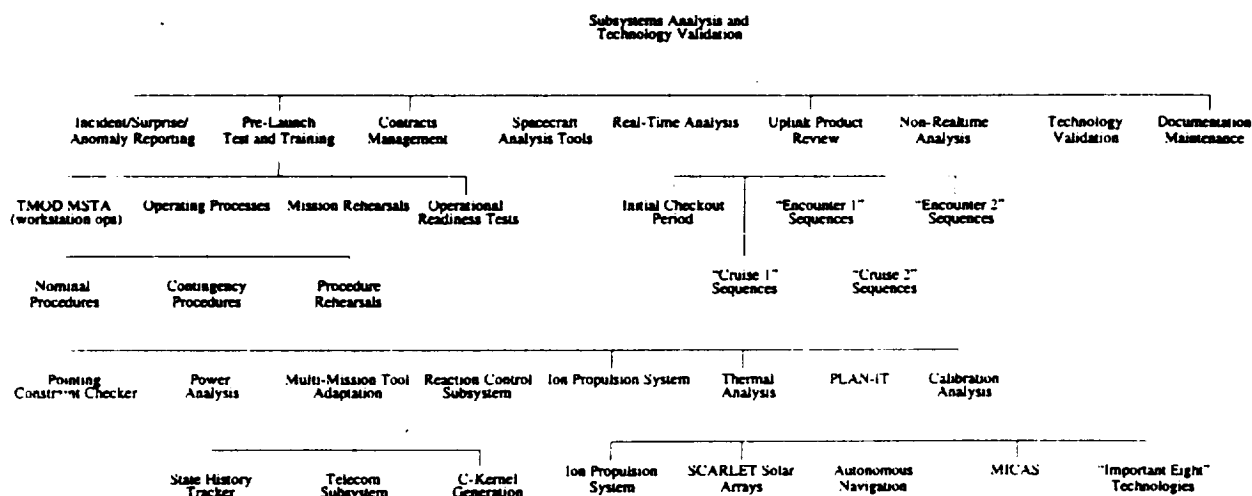


Figure 4 SATV Work Breakdown Structure

high-level task schedule, and contains an attached workforce/staffing chart. For further clarification, a Work Breakdown Structure (WBS) was also included in the package and is shown in Figure 4. Close inspection shows the omission of the system engineering and flight system testbed responsibilities, both of which fall in the FET domain. Finally, planned fiscal expenditures are documented in a Resource Cost Planner (RCP) approved plan which includes information on direct JPL labor, in-house and remote site contractor labor, travel, services, and procurement costs.

Ground Data System. The Mission Support Area (MSA) and the SATV Area (SATVA), both at JPL, provide proper facilities for the SATV team members to

time monitoring and/or non-realtime database queries in support of analysis tasks from workstations or desktop computers located outside of the firewall. This is a 'read only' implementation in that direct access to spacecraft commanding is not possible for obvious security reasons. Finally, as a convenience for remote site (e.g. industry partner and new technology provider) personnel a web-based tool was created to allow for similar 'read only' capabilities at these locations.

Spacecraft Analysis Tools. In addition to the ground data system, a set of software tools have been developed to assist analysts with the task of verifying uplink products such as real-time commands, files, and command sequences, and also for reduction of

downlinked telemetry data. This tool set is comprised of multi-mission software adapted for use on DS1 and software developed especially for DS1. The primary consideration for development and use of these tools again is to assist the analyst in being more efficient, providing for increased consistency, and simplifying the process, so that if necessary, others can be cross-trained to provide identical or similar results.

Team Members. A candidate team member list was provided to the SATV manager by the mission manager. This served as a baseline during the selection process, which was accomplished over several weeks. The SATV Manager sought to match technical and programmatic needs with that of personal skills and interest. It was recognized that due to the aggressive or compressed nature of the DS1 Project development life cycle schedule, there would be little time for comprehensive documentation that 'other' personnel could use as mission operations training references. It was decided that the most effective and efficient technical knowledge and expertise transfer mechanism was to transition a number of spacecraft development personnel to mission operations. Once the team members were identified, the first team meeting was held to review the WPA and RCP, so as to include all concerned parties into the team definition and development process to provide an important sense of ownership.

PREPARATION

Initial Training. In the January through May 1998 timeframe, SATV team members were engrossed in spacecraft development and test activities. In addition to the great deal of spacecraft mechanical, electrical, and overall system integration and testing activities occurring at the time, much of the flight software verification and validation was taking place in the Flight System Testbed, a high-fidelity environment utilizing flight spare and engineering model electronics hardware, electrical ground support equipment, and a spacecraft dynamics simulation described by (Basilio 1996 and Leang, et al 1997). Due to this immersion of activities, attempts at training individuals to use the ground data system 'tools' and even supporting the initial uplink product verification and validation process for activities scheduled during the first forty days of the mission generally did not succeed.

In June 1998, following the general co-location of project personnel and a leveling off, but still significant amount of spacecraft and flight software testing, a noticeable change was taking place. There was an

appreciable increase in interest associated with ground data system training and operating procedure development and rehearsals. In regards to ground data system training, the benefit soon became obvious with personnel becoming knowledgeable and proficient with the necessary tools for non-realtime analysis. The team had opportunities to practice with these 'tools' in supporting non-realtime analysis of spacecraft baseline functional testing during the final three months prior to launch.

In regards to operating process procedures, these documents constitute a majority of those that the team has been and will continue to follow during in-flight operations consistent with the "say what you do, do what you say" ISO (Industry Standard Organization) 9001 (Model for Quality Assurance in Design and Development, Production, Installation, and Servicing) guidelines identified by (Kasser and Williams 1998). It was not sufficient for these procedures to be documented. Rehearsals to verify and validate what was written also needed to be done.

Mission Rehearsals. The next phase in preparing the team for mission operations was to combine two or more of the operating process procedures into one of three planned mission rehearsals to not only further verify and validate what was written, but to also train the personnel responsible for carrying out a process or set of processes. The three mission rehearsals selected were associated with:

- Nominal Launch and Initial Acquisition
- Ion Propulsion System Turn-On
- Anomalous Launch and Initial Acquisition

As one can see from above, one of the three mission rehearsals included a simulated anomaly so as to provide an opportunity for the team to exercise the appropriate contingency plan or set of contingency plans. This was in recognition of the fact that preparing the team to handle anomaly situations was as important as preparing them for normal/nominal scenarios as indicated by (Basilio 1992). Timely anomaly diagnosis, resolution, and recovery is instrumental in allowing the flight team to continue meeting mission objectives.

Operational Readiness Tests. As a final step in the procedure verification and personnel training process, the three mission rehearsals listed above were rerun in more of a testing atmosphere. Successful completion of these events was necessary in assisting the MOS to be 'certified' for in-flight operations. In these instances, personnel who would actual be on

console or play an important role in the actual events were the participants in the appropriate test(s). A significant number of process improvements were identified and later implemented for execution of the actual activities.

PARTICIPATION

In the few months prior to launch, direct mission operations support was limited to uplink product verification and validation of the activities scheduled for the first forty days of mission operations. There was a marked improvement observed in the amount of support being given to this task as compared to the first attempt in the January to May 1998 timeframe. This was due to spacecraft development and test activities tapering off, the completion of ground data system training, operating process procedures having been developed and rehearsed, completion of the mission rehearsals, but probably most important, the acknowledgment that this was a critical task that needed to be completed prior to uplink and execution of these activities in-flight.

EXAMINATION

Flight Team Organization. As previously stated, the project organization chart experienced a change consistent with a shift in emphasis from spacecraft and ground segment development to mission operations planning and support. This is evidence of the fact that a project organization need not remain unchanged during the entire course of the development life cycle. A transition at the appropriate time assists the team in understanding the importance of completing the original assignments in a timely manner, so as to adequately prepare and train for the next important project phase. However, the project staff must make an accurate assessment of when this transition is to take place - too early and planned activities fail to be accomplished due to the unavailability of personnel, too late and planned activities still fail to be accomplished, this time due to lack of adequate time.

A balance of priorities must be maintained. Critical to this is the working relationship and the mutual understanding of these priorities between the spacecraft manager and the SATV manager. Although a negotiated transition can be defined and documented, enforcing such a position is only possible if identified in the WPA and RCP cost estimate, with personnel working on and charging to the appropriate account number. Finally, closely monitoring status and attentive listening when speaking with affected individuals provide indicators for the project staff to

make a well-informed decision - "everything in it's own time".

Personnel. Since the SATV Team is comprised of an aggregate of personnel representing typical spacecraft subsystems and who are primarily located at JPL, and also personnel representing new technologies, but who's primary work areas are at their employer's facilities, management of a team that is mainly co-located, but with some remote site participation comes with it's own set of challenges. Consistent motivation, effective and efficient communications, and necessary travel are some that come to mind. The SATV manager must understand that even with the advent of recent communication tools described by (Browning 1998) such as voicemail, electronic mail, interactive web-base tools, teleconferencing, and videoconferencing, effective relationships with remote site personnel require more time and effort than with a completely co-located team. This must be properly accounted for during the formulation process. Disregarding this fact will create an additional, but what could also be considered an artificial, barrier. (Wertz and Larson 1996) indicate that there is sufficient empirical data available to suggest that a relationship represented by

$$f=n^{0.2}$$

where f is the cost adjustment factor and n is the number of organizations, exists for projects that are not entirely co-located. For example, a JPL flight project with a single industry partner will result in a cost increase of approximately fifteen percent (15%) due to necessary communications needs.

To increase the probability of creating effective relationships, two items must be addressed. The first is defining explicit expectations between the remote sites and the core SATV team co-located at JPL. Not determining and understanding these responsibilities will lead to inaccurate assumptions and ambiguity eventually leading to confusion at what might be the most inappropriate time, during normal/nominal in-flight operations or worse yet, during anomaly diagnosis, resolution, and recovery. These expectations must not merely be written down and believed to be understood, they should also be exercised during the mission rehearsal and/or operational readiness test process, for clarity. Also, developing synergistic relationships with the other project elements should be considered mandatory for success.

Secondly, while most modern communication methods are now clearly understood and simple to use

(e.g. electronic mail), other methods require user guides, preferably brief and concise, for proper use. For example, remote access to the Sun workstation located on "No Man's LAN" or to the web-based database query tools require some configuration, a user's manual, and possibly some amount of training for proper use.

Finally, (Browning 1998) warns of the potential of overcommunication through the use of electronic mail, where users send information to large distribution lists (i.e. "spamming"). It's difficult for personnel to assimilate all messages. Examples where spamming has lead individuals to filter incoming electronic mail is becoming more and more commonplace. Future projects need to be aware of this situation and should seek to develop guidelines if this is chosen as the prime communications method.

The SATV manager must understand the important balance of available documentation and the technical knowledge and skills possessed by candidate personnel. While some positions require someone with general knowledge in a given subject area or set of subject areas, since accompanying documentation is readily available, others require more in-depth knowledge due to the lack of documentation and/or expertise required to properly utilize software tools. These are important considerations for the SATV Manager during the selection process.

Another obvious consideration is the matching of team skills needed and personal interest. Although the situation could be regarded such that personnel can be 'drafted' due to the priority level granted the DS1 Project at JPL, it's better to match needs and interests, because of personal motivation factor and how this might affect performance later on. Also, with JPL following a matrix organization model with most personnel reporting to both a project and line supervisor or manager, it is important that the SATV Manager work with the affected line supervision and management during the selection and assignment period definition process to obtain possible approval, but at the minimum concurrence level, on any workforce/staffing decisions made.

Schedule. One method used to reduce overall project cost is schedule compression. This reduces the overall workforce run-out total, which directly affects cost. This is an effective tool as long as risk trades and decisions can be made quickly, and as long it does not adversely affect the ability of personnel to make an effective transition from spacecraft development to mission operations planning and direct support. One

must understand if sufficient time is not allocated for this transition, personnel may not be adequately trained, ground software tools may not be properly verified and validated for operational use, operating process procedures may not be adequate or available, and generation and verification of initial uplink products may not be completed in a timely manner.

CONCLUSION

To reap the full benefit of the "faster, better, cheaper" concept, future space flight projects must follow guidelines consistent with this philosophy not only during the development life cycle, but also in the mission operations planning and actual support phase. The most important elements associated with the latter, and the former for that matter, are qualified personnel. Important human factor considerations during the much of the DS1 transition period have been identified and discussed. Some of the most important are related to including personnel in the team definition and development process to provide a sense of ownership, matching required skills and personal interests, providing adequate tools to do the job, providing test and training opportunities, and developing synergistic relationships at the SATV intra-team and inter-team levels, and finally, ensuring that schedule compression, if implemented, does not adversely affect the ability of personnel to make an effective transition from spacecraft development to flight operations.

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BIOGRAPHY

Ralph Basilio is a Project Element Manager currently serving as the DS1 SATV manager. He has held two previous positions on the DS1 Project, having served as both the spacecraft test manager and the deputy avionics manager during development. Prior to his DS1 Project assignments, he was the Mars Pathfinder flight system testbed manager and cognizant engineer of the Attitude and Information Management Subsystem electrical ground support equipment, integration and test, and flight operations planning areas. Prior to that he was the Cassini Attitude and Articulation Control Subsystem (AACS) flight operations planning cognizant engineer; Galileo AACS unit lead, task leader, and analyst; and a United States Space Shuttle structural stress and thermal analyst. He is a recipient of six NASA Group Achievement Awards.

Ralph Basilio is a graduate of the California Institute of Technology's Engineering Management Program. He also holds a Master of Science Degree in Aerospace Engineering with a technical specialization in Astronautics from the University of Southern California, and earned his Bachelor of Science Degree in Aerospace Engineering with an emphasis in Applied Mechanics and Control Systems from the California State Polytechnic University.

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